

# **Gas Bubble Growth in Muddy Sediments**

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## **LONG-TERM GOALS**

Our long term goal is a quantitative, mechanistic and predictive understanding of the dynamics of bubbles and bubble populations in marine sediments. We believe this information can be used to improve and test acoustic backscatter models for sediments and better understand the ebullitive flux of methane, an important “greenhouse gas”, to the atmosphere.

## **OBJECTIVES**

The immediate objective is a working model for the growth of a single, isolated bubble in a marine sediment, validated with bubble growth data obtained in laboratory studies and with in situ data.

## **APPROACH**

We have a strategy of coordinated laboratory and modelling research to achieve our objective. The laboratory work (directed by Bruce Johnson and assisted by Bruce Gardiner and Regine Maass) aims to determine the size that bubbles can attain in sediments, internal variables like pressure, and the dynamic response of sediments to bubble growth. The modelling research (Bernard Boudreau and Bruce Gardiner), guided by the laboratory results, is developing appropriate model(s) for observed bubble growth.

## **WORK COMPLETED**

During the second year, significant advances have been made in theory and experimental observations.

## **RESULTS**

**A. Theory/Modelling.** With regard to theory, we now have a plausible theory for the overall control on the rate of bubble growth. Specifically, observation of bubbles in freshwater estuarine and coastal marine sediments indicates that bubbles below 10 cm depth grow on seasonal time scales (primarily

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May-October). We have developed a diffusion-reaction model that describes the dynamics of methane formation, its diffusion through porewaters, its incorporation into a bubble, and the consequent growth of the bubble. The model produces an explicit equation for the radius of a growing bubble,  $R(t)$ , with time using mean parameter values and under the assumption that the growth is ultimately controlled by diffusion of the gas from the sources:

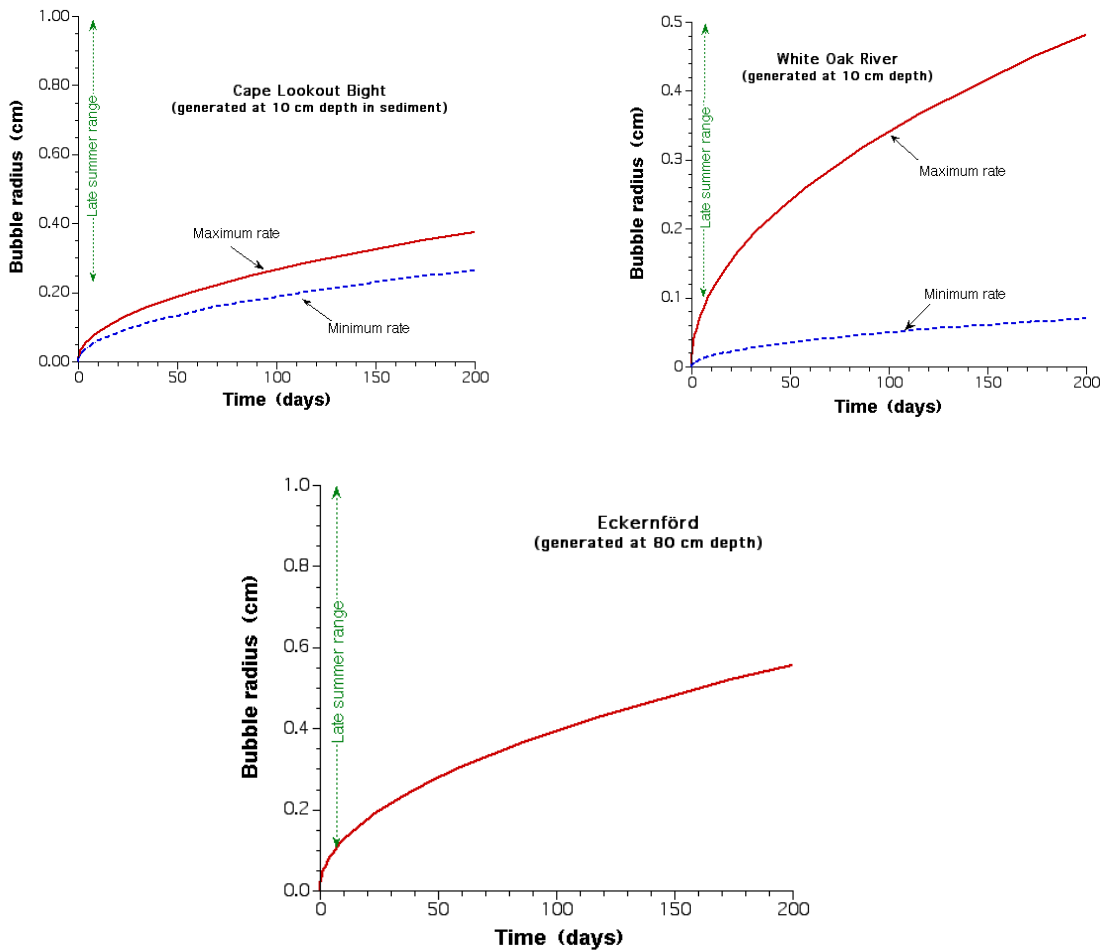
$$R(t) = \frac{ND}{2c_g} \sqrt{\frac{SR_1^2}{3D}} + (c_1 - c_0) A t + R_0^2 \quad (1)$$

where  $N$  is the porosity,  $D$  is the tortuosity-corrected diffusivity,  $c_g$  is the concentration of gas in the bubble,  $S$  is the local rate of methanogenesis,  $R_1$  is the separation distance between bubbles ( $R_1 \gg R$ ),  $c_1$  is the ambient concentration of  $CH_4$ ,  $c_0$  is the porewater methane concentration at  $R$ ,  $t$  is time, and  $R_0$  is the initial radius of the bubble, if not zero. The effects of the diagenetic source  $S$  and the level of super-saturation ( $c_1 - c_0$ ), thus, appear as separate contributing terms, and this formula can then be applied even in those cases where apparently  $c_1 = c_0$ . The latter point constitutes a significant new contribution to the theory of bubble growth.

We applied our model to three sediments where bubbles have been previously studied, i.e. Cape Lookout Bight (USA), White Oak River (USA) and Eckernförde Bay (Germany), see figure 1. In all three cases, using the site-specific time-averaged parameter values, the model predicts seasonal growth rates, consistent with the observations. Furthermore, the source term dominates the rate of growth at the first of these two sites, while diffusion from the ambient supersaturation dominates at the German location. Real bubbles may follow a more complicated growth history than predicted by the above equation because of the mechanical properties of sediments (see below); nevertheless, the overall growth times should be concordant with ultimate diffusion control from the diagenetic methane source.

The model was expanded to account for the effects of "rectified diffusion", the pumping of gas into a bubble by pressure oscillations, e.g. from waves and tides. This effect appears to be negligible due to the low frequency of these types of oscillations.

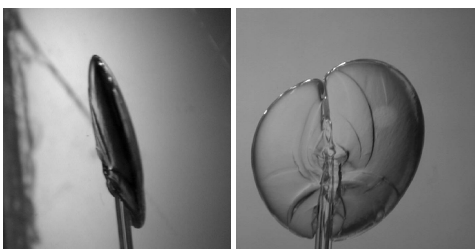
The theoretical work in year three will center on including the mechanical behaviour of sediments, which affects the shape of the growth history curve, as in figure 1.



**Figure 1:** Growth histories of bubbles in sediments from Cape Lookout Bight, NC, USA (top left), White Oak River, NC, USA (top right), and Eckernförd, Germany (bottom). Observed sizes of bubble at the end of the summer/fall growth period at each site is also indicated. The theory, eq (1) above, provides a reasonable explanation for the observed bubble sizes, except perhaps the largest sizes; however, the larger bubbles are probably the result of coalescence of smaller bubbles or intense local methanogenesis not fully accounted for by the mean value of  $S$  used here.

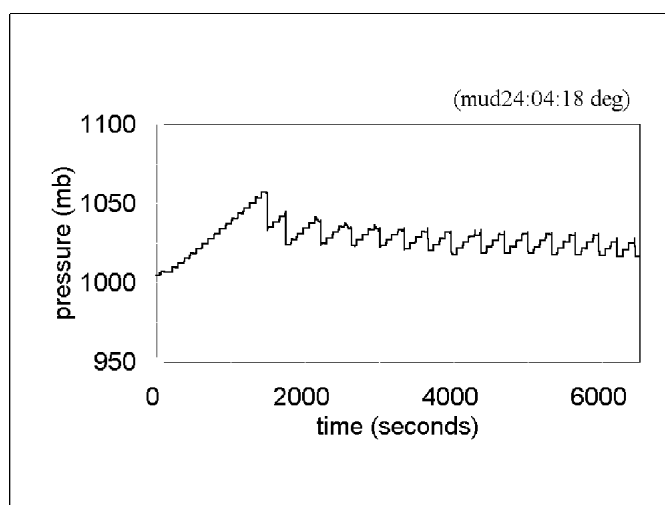
**B. Experimental Work.** In order to study the nature of bubble growth in sediments, we have injected bubbles through a fine glass capillary into sediment samples, and have followed stress and strain during bubble growth through monitoring bubble internal pressure. Shape information has been obtained through x-ray images and from performing the experiments in surrogate materials such as gelatin. X-ray images of sediment samples in which gas has been injected show that bubbles are not spherical in shape. Instead the horizontal cross-section of the gas inclusions formed at the capillary tip are in the shape of a crack. This result is consistent with other observations (e.g., results of x-ray tomography, Eckernförde Bay, Germany) in which many of the bubbles in natural sediments were found to be coin or disk-shaped with the long axis oriented vertically. Gas injected into gelatin, results in formation of

disk shaped bubbles at higher gelatin concentrations (2X) (figure 2) and a shape approaching spherical at low concentrations (1/2X).



***Figure 2: Disk-shaped (2 cm high) bubble formed at the tip of a capillary in 2X gelatin (left: side view; right: front view)***

Gas injection into sediment samples shows two types of stress-strain behavior: pressure rise, to the point of bubble injection, followed by bubble growth as pressure cycles through regular rises and falls in a sawtooth pattern (figure 3); pressure rise to the point of bubble injection followed by a smooth, gradual decline as the bubble grows. These appear to be two end members, as combinations of these two types of behavior are common. Bubble growth in the surrogate (gelatin) samples shows the same types of stress-strain behavior, with that as in figure 3 observed for the 2X concentrations and the smooth response in the less concentrated samples.

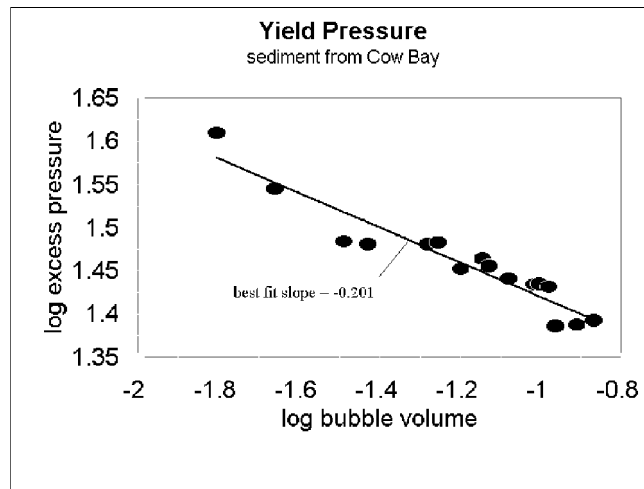


***Figure 3: Pressure record for injection of gas through a fine capillary into a sediment sample from Cow Bay, N.S. at 18 EC***

The results shown in figure 3 can be understood in terms of linear elastic fracture mechanics (LEFM). From LEFM, (Sneddon, 1946; Irwin, 1962; Green and Sneddon, 1950) we have derived an equation that relates critical pressures,  $P_c$  for bubble growth (the peaks in figure 3), to bubble volume at fracture,  $V_c$ , and properties of the sediment or surrogate medium. This relationship is

$$P_c = [K_{Ic}^{6/5} B^{4/5} (1/12)^{1/6}] / (E^{1/5} V_c^{1/5}) \quad (2)$$

in which  $K_{Ic}$  is critical stress intensity factor and  $E$  is Young's Modulus.  $K_{Ic}$  is a material property and the determinant of bubble growth behavior. According to equation 1, plotting  $\log P_c$  against  $\log V_c$  should give a straight line with a slope of  $-1/5$  and an intercept of  $\log (1.65 K_{Ic}^{6/5} / E^{1/5})$ . From this intercept,  $K_{Ic}$  can be determined and used to model bubble growth. Note that  $E$  must also be known, however, as it only appears to the  $1/5$  power, bulk values can be used with little error. Figure 4 shows the log-log plot of the critical pressures at fracture,  $P_c$ , (the peaks in the pressure record of figure 3) against bubble volume at fracture,  $V_c$ . Note that the slope is nearly  $-1/5$ . Bubble volume during gas injection is determined in two ways: first, if  $PV$  is conserved, bubble volume can be inferred knowing the pressure and the dead volume of the system; second, the gas injection is made in well defined discrete volume increments, and thus, each  $dP/dV$  and the dead volume can be used to determine the instantaneous bubble volume. The first method is not sensitive to changes in the total number of moles of gas, but the second makes no assumptions about the number of moles in the system and consequently, processes such as mass transfer and gas leaks do not introduce error.



**Figure 4: Plot of  $\log P_c$  against  $\log V_c$  for Cow Bay sediment sample: No. 24:04:18 showing a slope of approximately  $-1/5$**

Also from LEFM, the troughs in the pressure record of figure 3 can be understood in terms of crack arrest. The pressure rises to  $P_c$ , and then falls below this critical pressure because of the kinetic energy contribution to crack growth.

Having solved the problem of growth of a spherical bubble by diffusion from a distributed methane source, we have turned to solving the problem of growth of a non-spherical bubble. In particular, the Laplace equation is solved for the case of a distributed source in the oblate spheroidal coordinate system. This model is appropriate for treating bubble growth through fracture as has been observed in the laboratory experiments, and our goal now is to determine if the model can reproduce injection results such as those in figure 3.

## **IMPACT/APPLICATIONS**

Bubbles seriously compromise acoustic sensing of sediments, e.g. locating naval mines. Gas ebullition of methane is a major release mechanism to the atmosphere for this greenhouse gas. Thus, understanding bubble formation (and latter movement) constitutes an important practical and scientific problem. Our findings provide information that could help remove/filter bubble-produced acoustic signals and place limits of the flux of methane to the atmosphere.

## **RELATED PROJECTS**

We are not formally cooperating with any particular ONR funded project, but we hope to integrate our study with work being done in the Bubble-Acoustics DRI in the future.

## **REFERENCES:**

Abegg, F., A. Anderson, L. Buzi, A.P. Lyons and T.H. Orsi 1994. Free methane concentration and bubble characteristics in Eckernförder Bay, Germany in: Forschungsanstalt der Bundeswehr für Wasserschall- und Geophysik (FWG); T.F. Wever, Editor., 84-89.

Boudreau, B.P., B.S. Gardiner and B.D. Johnson. Rate of Growth of isolated bubbles in sediments with a distributed source of methane; *Limnol. Oceanogr.*, in press.

Green, A.E. and I.N. Sneddon 1950. The stress distribution in the neighborhood of a flat elliptical crack in an elastic solid. *Proc. Cambridge Philosophical Soc.*, 46, 159-164.

Irwin, G.R. 1962. The crack extension force for part-through crack in a plate. *Trans. ASME. J. Appl. Mech.*, 651-654.

Sneddon, I.N. 1946. The distribution of stress in the neighbourhood of a crack in an elastic solid. *Proc. Roy. Soc. London A*, 187, 229-260.